Readout for Phase Qubits without Josephson Junctions

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We present a novel readout scheme for phase qubits which eliminates the read-out SQUID so that the entire qubit and measurement circuitry only requires a single Josephson junction. Our scheme capacitively couples the phase qubit directly to a transmission line and detects its state after the measurement pulse by determining a frequency shift observable in the forward scattering parameter of the readout microwaves. This readout is extendable to multiple phase qubits coupled to a common readout line and can in principle be used for other flux biased qubits having two quasi-stable readout configurations.

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The reliable identification of the quantum state occupation probability of a qubit with high fidelity without introducing detrimental system complexity has been at the center of attention in the design and operation of superconducting qubits in recent years[1–4]. Over the years these trade-offs were optimized for various types of qubits to enhance overall qubit performance [5–7]. Although some of these new methods could also apply to the phase qubit, measurement techniques for these qubits have remained largely unchanged. The switching of a two or three Josephson junction SQUID into its normal state remains the main technique to identify the qubit state of a phase qubit [8–10].

In this letter, we show a novel phase qubit read-out method [11] which eliminates the SQUID and its associated dissipation entirely [3]. By removing the SQUID we also reduce the number of required Josephson junctions from three or four to only a *single* Josephson junction, thereby dramatically improving the overall device yield.

The measurement of phase qubits is typically done in two steps (e.g. [12]). First, the quantum state is "measured" by taking advantage of the potential energy landscape such that post measurement the system is in one of two quasi-stable configuration depending on the quantum state prior to measurement. This step has been demonstrated with large single-shot fidelities and reliable performance [9]. Finally, the qubit is "read out" by identifying which of the quasi-stable configurations the system is in. By convention we refer to these configurations as the left (L) and right (R) configuration. Because the L and R configurations correspond to a large difference of the circulating current in the qubit, the obvious choice has been to flux couple a SQUID to the qubit and detect the current at which a SQUID switches to its voltage state. The configuration, L or R, can be identified with high confidence using the SQUID, usually without significant backaction. Recently, however there has been mounting evidence that the SQUID does indeed limit qubit coherence times or at least drastically impacts the repetition rate of the experiment [3, 13].

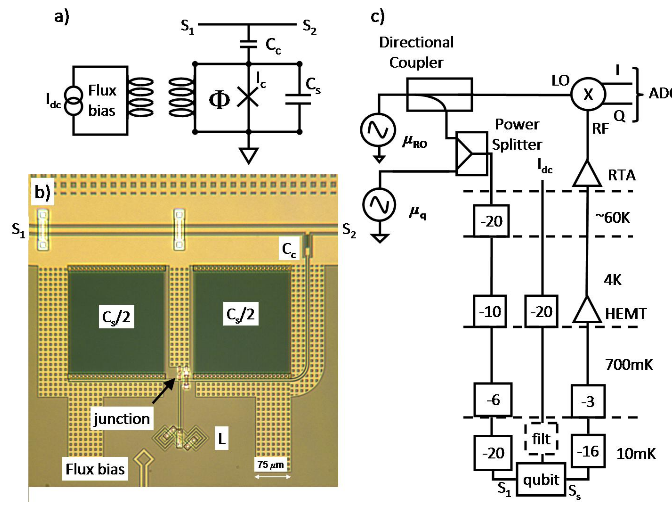

FIG. 1: Outline (a) and micrograph (b) of the qubit. The phase qubit consists of the standard circuit elements in parallel - a Josephson junction, an inductor and a capacitor all capacitively coupled to a feedline via a coupling capacitor. An optical micrograph of the qubit depicts the actual layout of circuit. c) Shows the readout schematic, The qubit flux bias and microwave lines (S1,S2) are sufficiently filtered and attenuated to ensure sufficiently low electron temperatures. A HEMT at the 4K stage amplifies the outgoing microwave signal.

Because the L and R configurations in a phase qubit have dramatically different resonance frequencies we propose to identify the system configuration by probing the qubit with microwave pulses using dispersive techniques [5–7]. We estimate that the correct identification of the L or R configuration is possible with high certainty given read-out times comparable to those using the SQUID. The new technique is made possible by directly coupling the qubit to a microwave feedline and probing the amplitude or phase response of a microwave pulse that passes by the qubit. The new readout is compatible with all existing state-of-the-art phase qubit techniques, including reset and measurement.

We have successfully implemented the most basic operations of this microwave based read out technique. Here we present our experimental results and speculate on further improvements. Because the operation and "measurement" of the phase qubit does not change dramatically in our implementation we are able to base our design on published literature [9, 10, 12]. The basic layout of the qubit circuit is shown in Fig. 1a. We chose a capacitively shunted phase qubit to minimize the number of junction two-level systems in the qubit spectroscopy and maximize measurement fidelity [14]. In order to ensure long coherence times of the qubit we fabricated the shunting capacitor using an interdigitated comb with the ends shorted together to eliminate parasitic cavity modes [13]. The target value for the shunting capacitor is $C_s = 2$ pF. The qubit loop is designed gradiometrically with $L = 625$ pH to eliminate sensitivities to stray flux variations and reducing flux coupling to the microwave feedline. The coupling capacitor is chosen to be $C_c = 23$ fF which should limit T_1 to about $T_{1,feed} = 2C/(Z_0(\omega C_C)^2) \approx 180$ ns for a qubit frequencies near 4.6 GHz [15].

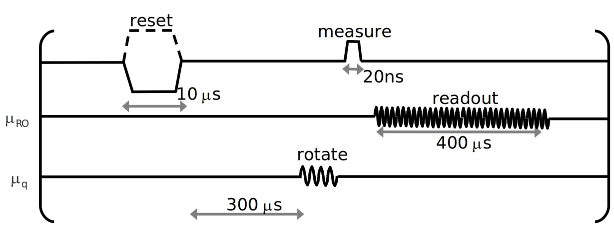

FIG. 2: Experimental pulse sequence. The flux bias Φ and qubit microwave pulse μ_q follow standard phase qubit protocols. The microwave read-out pulse μ_{RO} is applied after the measurement pulse is executed for a duration of $400\mu s$.

The fabrication was similar to ref [16]. An optical micrograph of the fabricated qubit is shown in Fig. 1b. The sample was mounted inside an RF-tight box and cooled down in a dilution refrigerator. The bias lines were configured as outlined in Fig. 1c. The flux bias line is filtered with a low pass bronze powder filter, matched to $Z_0 = 50$ Ω impedance, with a 1 GHz cut-off frequency [17].

The qubit is calibrated by executing a pulse sequence similar to the one shown in Fig. 2. A reset pulse is applied to the flux line and added to the flux bias line via a DC-block at room temperature. However, neither the microwave pulse "rotate" nor the subsequent measurement pulse "measure" is applied to the qubit. The microwave readout signal μ_{RO} is mixed with itself rather than a separate microwave source tuned to the same frequency to eliminate phase drift between the microwave generators. The resultant I and Q signals at DC are filtered and digitized using an Acqiris data acquisition board and averaged on board using sufficient averages for acceptable signal-to-noise ratios. We then plot the amplitude response $|I + iQ|$ versus flux in Fig. 3. To better visualize the results we plot the negative amplitude for a negative reset pulse (black) and the positive amplitude for a positive reset pulse (white). Whenever the qubit is hysteretic (between 0 and $\approx 0.45\Phi_0$) the frequency response is vastly different depending on which reset pulse was applied, showing that the L and R configurations have very different resonant frequencies.

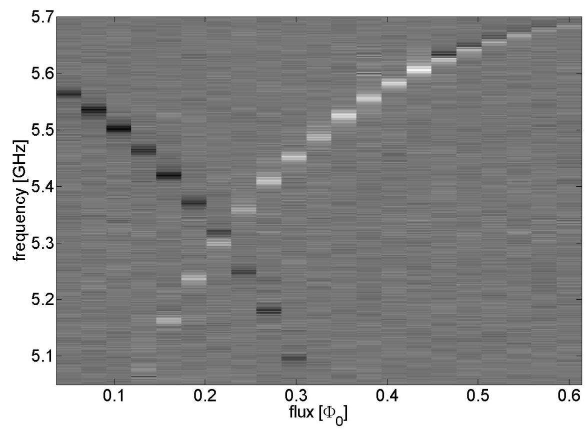

FIG. 3: Frequency response of the phase qubit for negative (black) and positive (white) reset pulses. When the qubit is hysteretic two resonance frequencies are observed, consistent with the L and R configurations. The lower frequency response ω_L corresponds to the configuration in which the qubit is operated, and the other, ω_R, corresponds to the configuration in which the phase particle tunneled during the measurement pulse. The read-out is performed by observing the presence or absence of resonance response at ω_R.

We now set the DC flux to $0.425\Phi_0$ which is close to the edge of where hysteresis observed. Depending on the reset pulse two resonance frequencies can be observed. The lower one corresponds to the configuration in which the phase is located in the shallow well (L configuration) - this is the configuration where the qubit is operated. The higher one, ω_R, corresponds to the R configuration. We are interested in ω_R because this is the expected resonant frequency after the phase tunnels from the L to R configuration during measurement. From here on all experiments follow standard phase qubit protocols with the only difference being how the signal is measured. In this case we measure the amplitude response at ω_R with respect to the reference, defined by the result obtained when the measurement pulse is absent. In principle we only need to calibrate the reference once, but we obtain improved results by continually recording the reference value because of small drifts. Also note since we choose to average the homodyne voltage on the data acquisition card, we are not performing a single shot read out. Due to the 19 dB of attenuation the signal is reduced almost a factor of ten so that the high fidelity single shot acquisition times for μ_{RO} would have been prohibitively

long (10 ms assuming the experiment is limited to the noise generated by the HEMT). By replacing the attenuators with properly designed isolators it will be possible to reduce the required acquisition times to $100 - 500$ μs, comparable to those using a SQUID based single-shot read out.

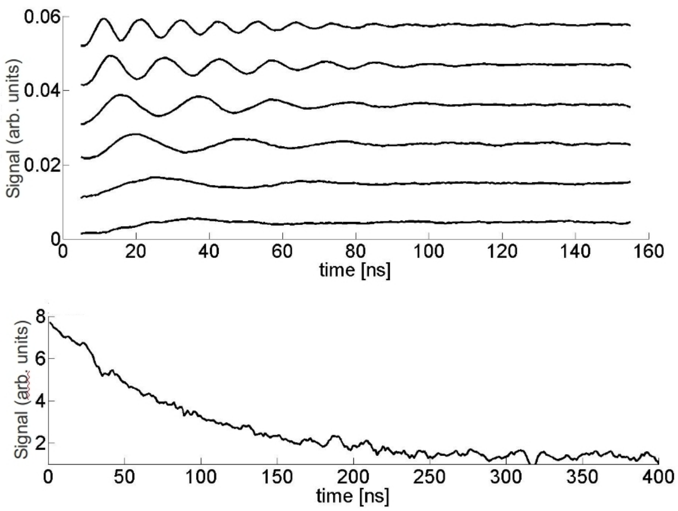

FIG. 4: Rabi oscillations and an energy relaxation curve of the qubit. Note that no absolute scale is shown as we are presently not performing a single shot measurement.

Following standard phase qubit pulse sequences we are able to characterize the qubit. We show in Fig. 4 the results for Rabi oscillations and a T_1 experiment for a qubit frequency of $\omega_L/2\pi = 4.46$ GHz ($\omega_R/2\pi = 5.6$ GHz). The energy relaxation time T_1 is found to be approximately 83 ns. We believe this value is limited by $T_{1,feed}$ because a separate sample using a SQUID based read out gave $T_{1,instrinsic} = 260$ ns and because $(1/T_{1,intrinsic} + 1/T_{1,feed})^{-1} = 106$ ns is close to the observed coherence time. An improvement in T_1 should therefore be possible by simply reducing the size of the coupling capacitor.

We have clearly demonstrated the basic principle of a new microwave method of reading out phase qubits. It is instructive to discuss how the current implementation relates to other experimental practicalities as well as to scalability. The most significant drawback of our technique is the fact that the T_1 times of the qubit are somewhat affected by the coupling to the feedline. This is perfectly acceptable, however, if one is interested in studying qubit spectroscopy [18]. However, because of the large size of frequency shifts for the L and R configurations we believe that it should be possible to also circumvent this limitation. By coupling the qubit to other linear elements we estimate it should still be possible to observe a frequency shift dependent on the qubit configuration without limiting coherence times [13]. We note that our proposed scheme is a step towards multiplexing many phase qubits off a single feedline, similar to readout schemes for photon detectors [19].

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